# A Fresh Perspective on Cold Nuclear Matter Effects

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→ **Shadowing, energy loss and multiple scattering**

## Why should you care about nuclear effects?

1. **Nuclear effects provide significant background for A-A collisions, especially at forward rapidities.**
2. **Effects are large - factors of two or more suppression versus p-p**
3. **Fundamental physics -**
   - **Form and magnitude of partonic energy loss is unknown.**
   - **Origin and magnitude of shadowing is unknown -**
     - **models : initial state suppression, gluon recombination**
     - **final state, dynamical coherent scattering**
   - **Multiple scattering of partons - Cronin effect**
   - **Fragmentation and formation time effects - quark mass effects**

Los Alamos

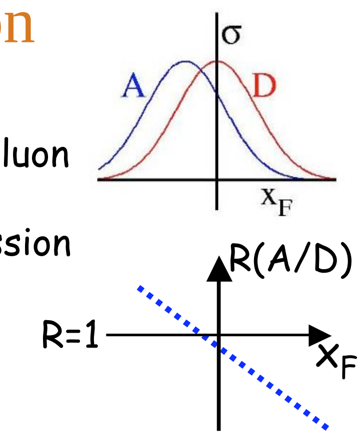
**PHENIX Forward Upgrade Meeting, Santa Fe, May 15, 2007**

# Problem : Nuclear dependence of J/ψ
## $g+g \rightarrow c\bar{c}$ (small $x_F$) or $q+\bar{q} \rightarrow c\bar{c}$ (large $x_F$)

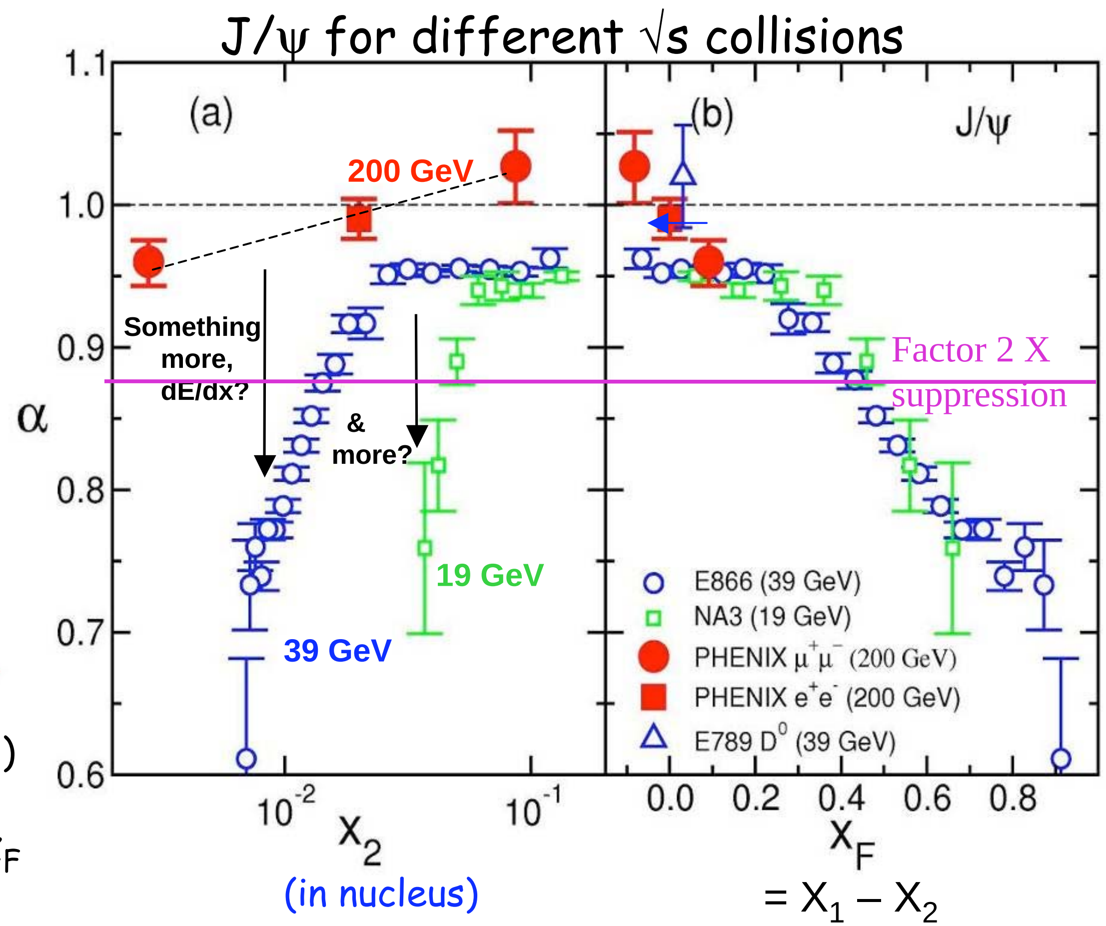
- Suppression doesn't scale with $x_2$
  $\rightarrow$ not shadowing
  In fact, no evidence for any gluon shadowing!

- Scales with $x_F \approx x_1$
  $\rightarrow$ large energy loss of incoming parton

**Energy loss** of incident gluon shifts effective $x_F$ and produces nuclear suppression which increases with $x_F$



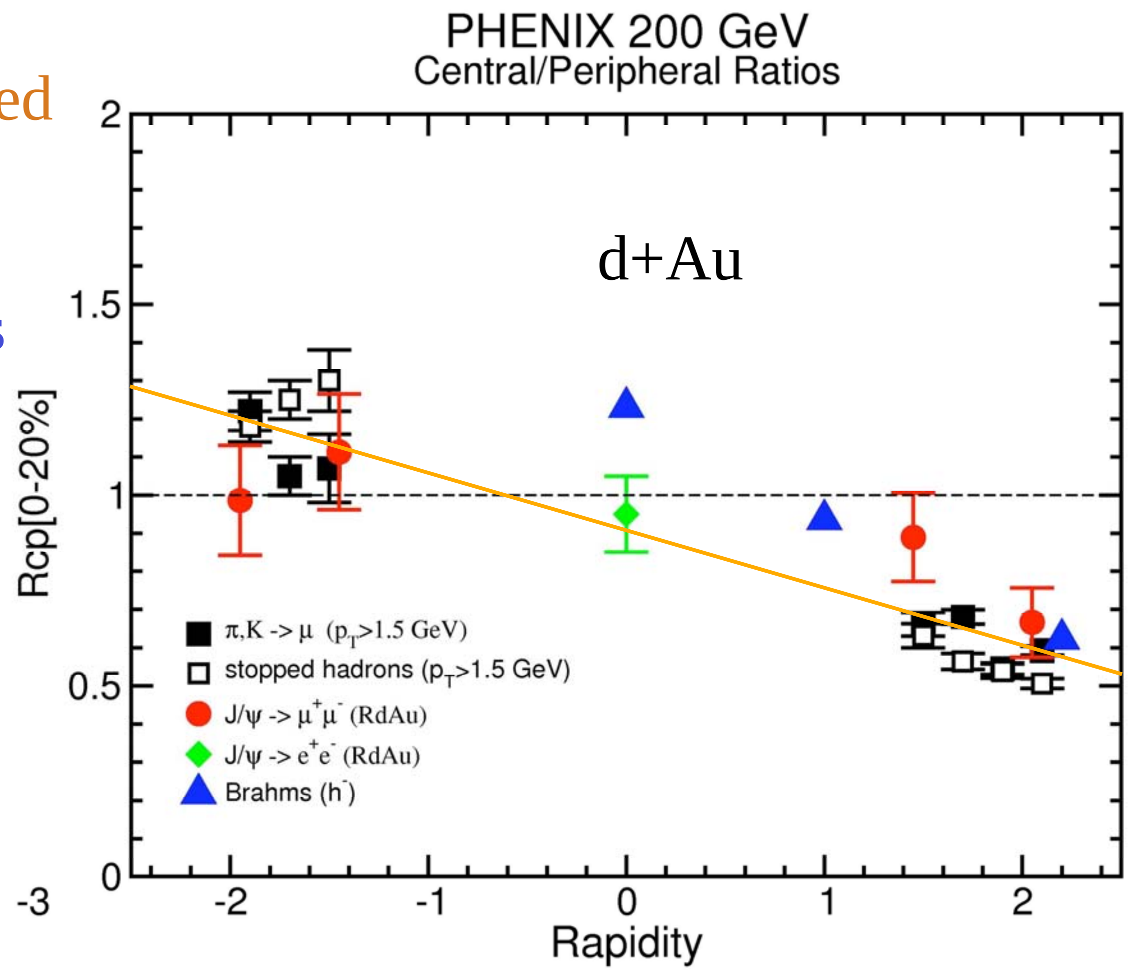

$$\sigma_A = \sigma_N A^\alpha$$ *PHENIX PRL 96, 032001 (2006)*



# Universal behavior of nuclear dependence for light and heavy quarks?

- Forward rapidity suppressed
- Backward enhanced
- No suppression at y = 0 !
- Charm behavior ~ same as light quarks, yet x values should be much higher?

Looks like energy loss (rapidity shift) !



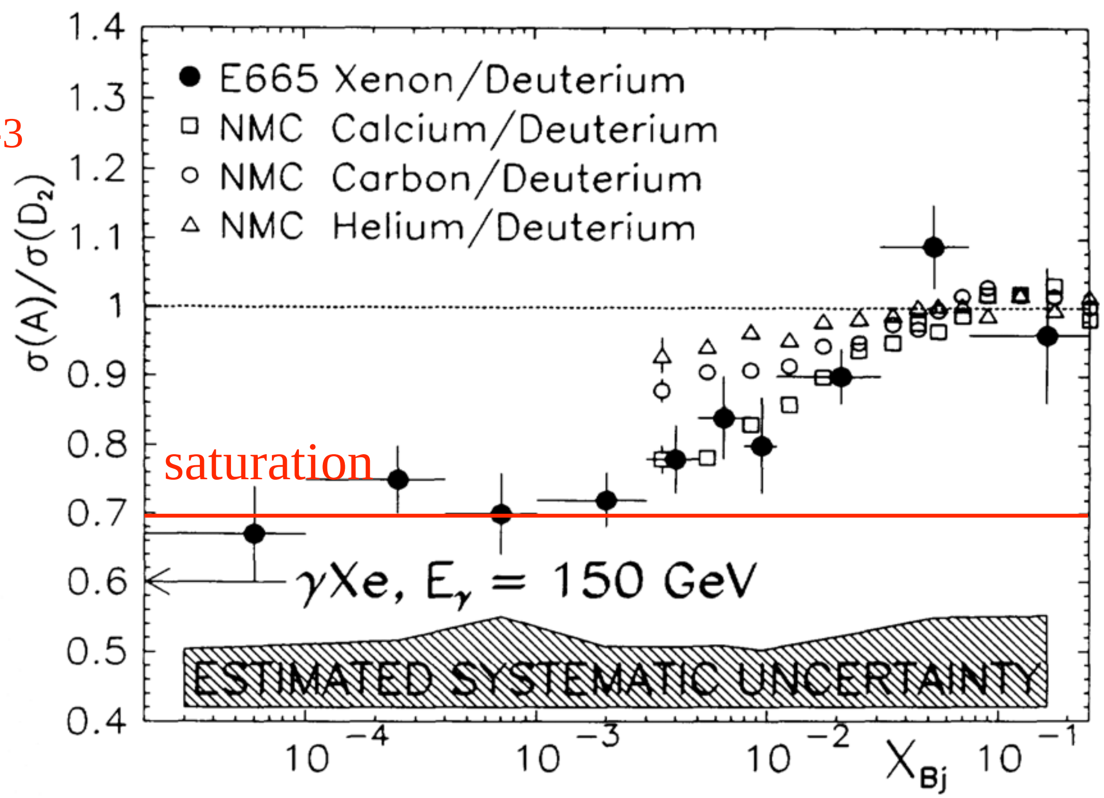
# Why do we expect shadowing of gluons?

## Well known for sea quarks from DIS

- 30% suppression in Xe
- Saturates at below $x = 10^{-3}$
- May saturate at large A
- No direct measurements for gluons
- No E loss in DIS

Origin? unclear :

- spin 1/2 (fermions) $\rightarrow$ pauli blocking
- dynamical rescaling
- nuclear binding
- etc.




x (nucleus)

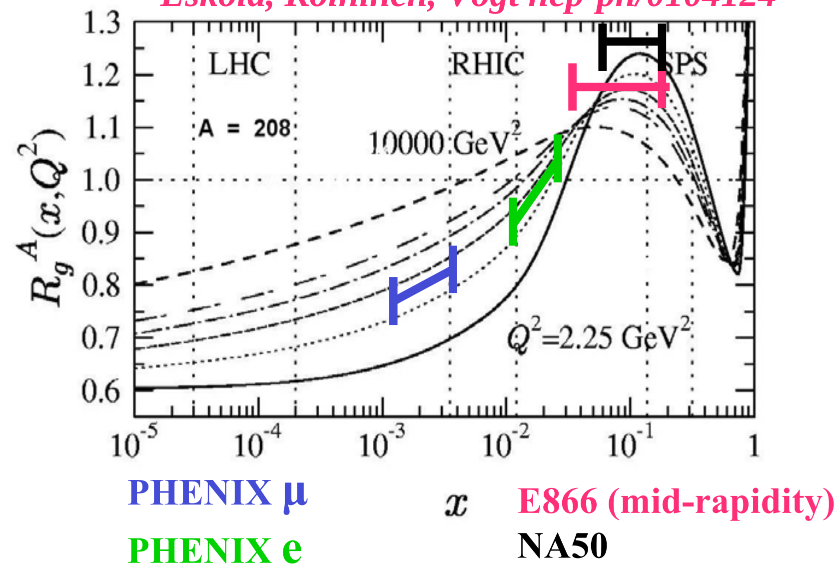
# What about gluon shadowing ?

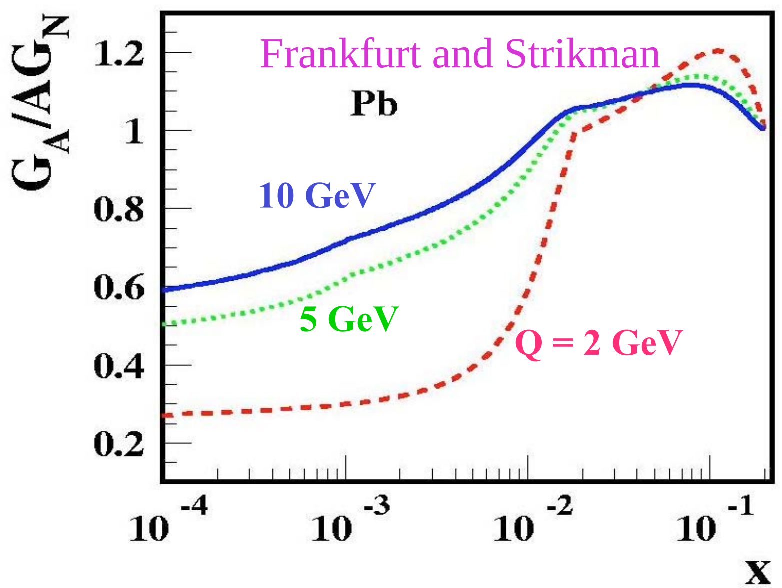
Have EKS parameterization, issues -
- Based on fits to quark shadowing
- Large dependence on $Q^2$
- Not much predictive power

Several theoretical approaches :
- Leading twist shadowing (Frankfurt and Strikman)
- Higher twist color dipole (Kopeliovich and Tarasov)
- Dynamical rescaling (Vitev)
- Color glass condensate

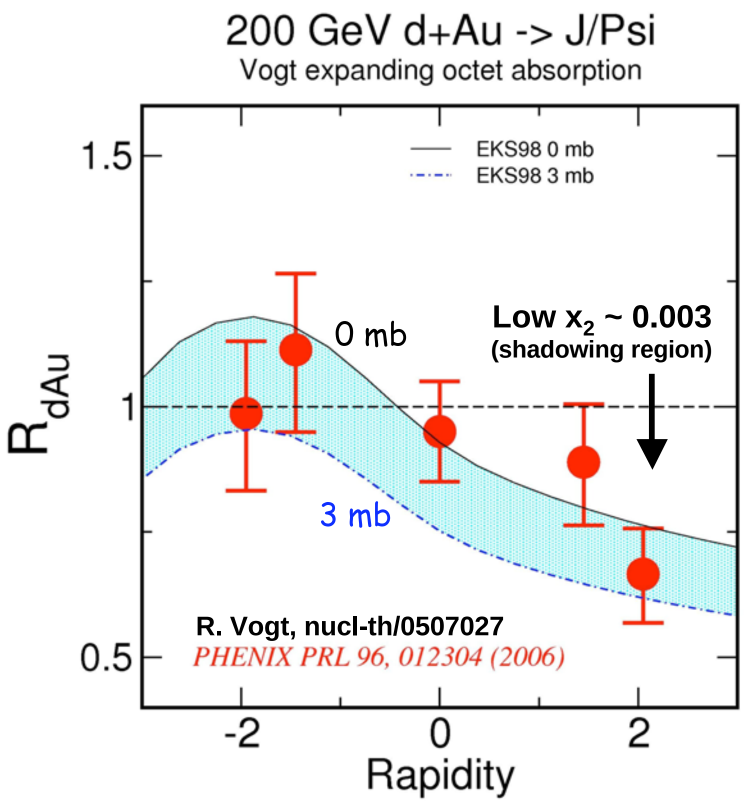
Factor of 3+ range in suppression between different models!

*Eskola, Kolhinen, Vogt hep-ph/0104124*

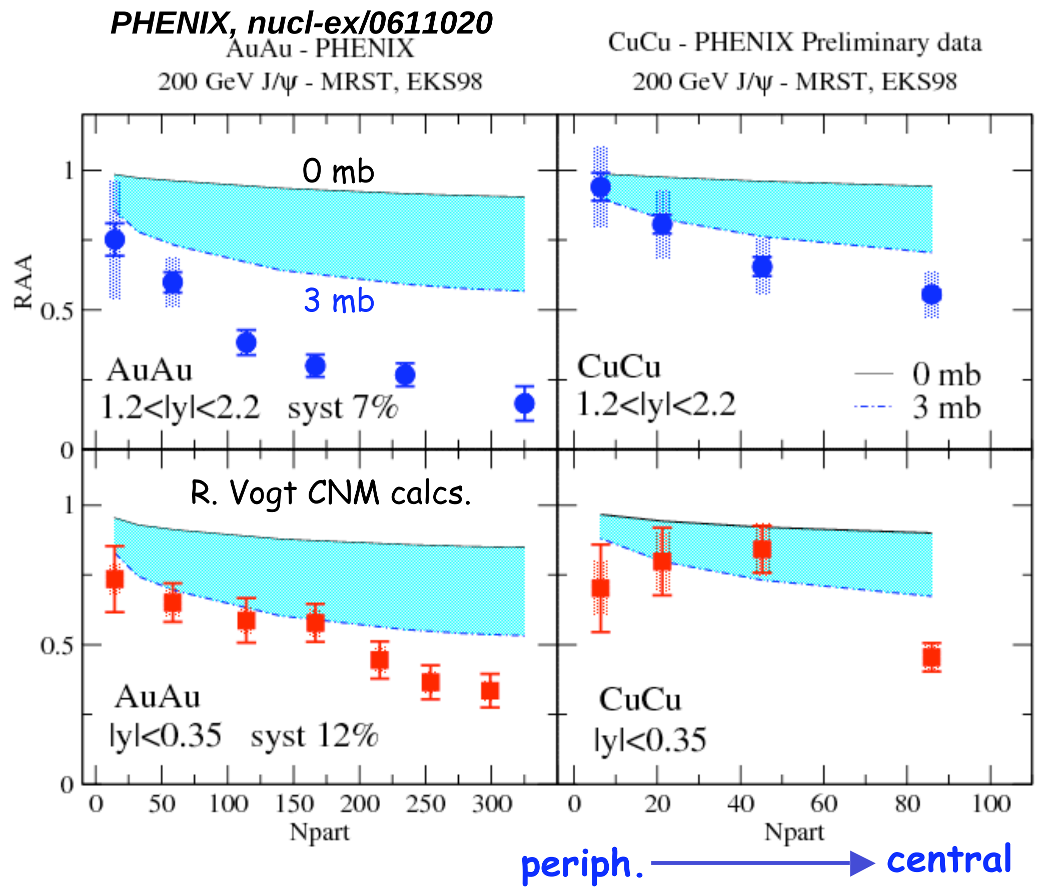


# J/ψ suppression in p+A and A+A collisions




Absorption : J/ψ + X → DD




Shadowing alone (EKS 0 mb curves) seems to have little effect on A+A reactions

→ Either large absorption or energy loss seems required for A+A

# How about energy loss?

Fits to Drell-Yan data give an initial state quark energy loss of :

$\Delta E$ ~ 2.5 to 5 GeV / fm, but:

- Very dependent on shadowing and Cronin correction for anti-quarks.
- No insight on energy dependence
- Consistent with :

$\Delta E$ ~ 0 GeV for EKS shadowing

Nuclear dependence is stronger for $J/\psi \rightarrow$ much larger E loss for gluons?

Theory :

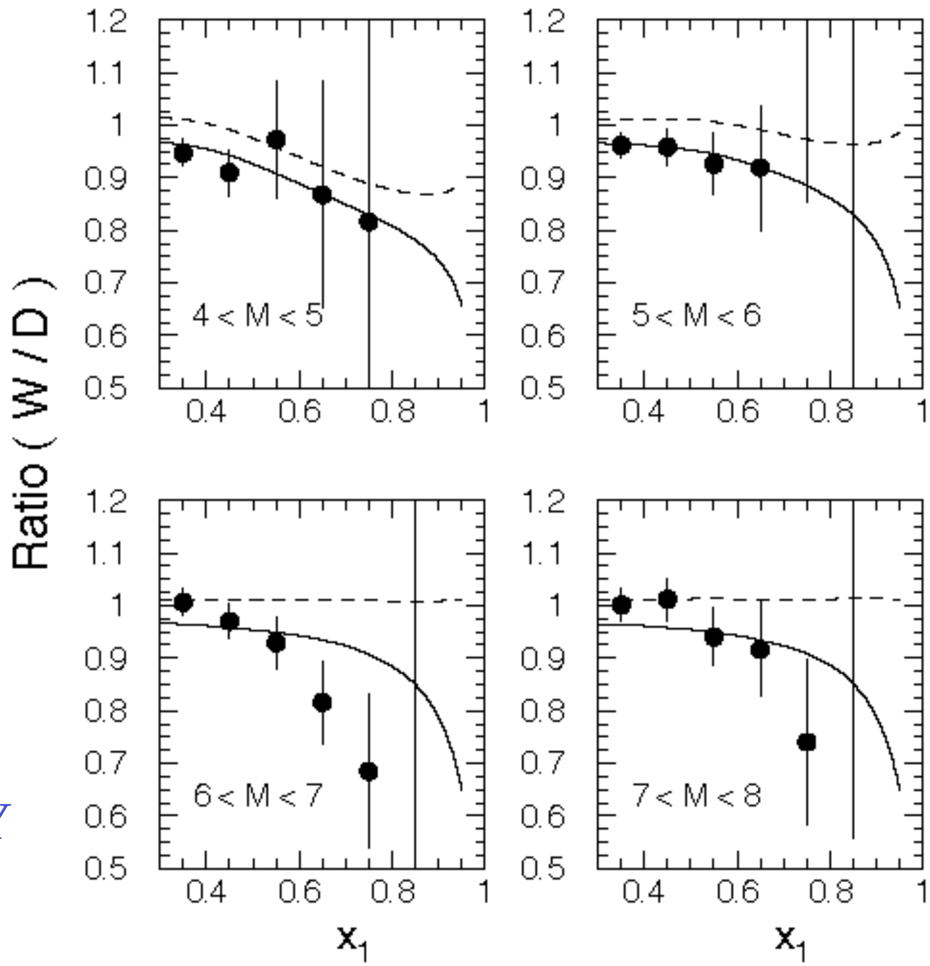
- Gavin and Milana - $\Delta E$ ~1.5 GeV / fm
- Baier et al (BDMPS) -

  $\Delta E \propto \Delta p_T^2$, $\Delta E \propto L^2$ both small for DY
- Vitev - LPM

$$-\Delta E \propto \alpha_{\text{strong}} \times \left[\frac{L}{\lambda}\right] \times [E]$$

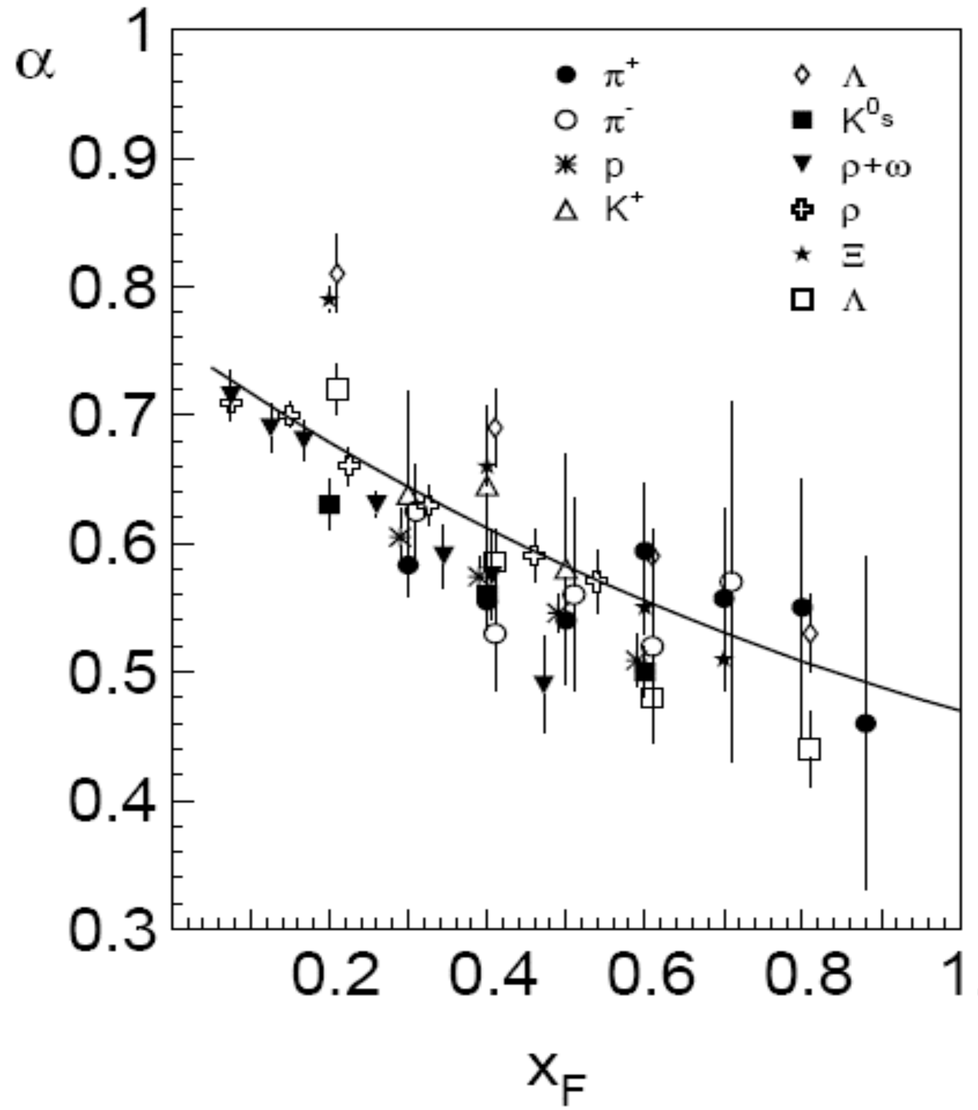
- Kopeliovich et al - Sudakov suppression

E772 p+A→Drell-Yan



# Universal scaling versus $x_F$

- p+A → X, many √ S, A
- Universal scaling with α, yield ∝ $A^{\alpha}$
- Sudakov suppression calc from Kopeliovich et al. (equivalent to energy loss)
- Not much room left for shadowing!



# Multiple Scattering of quarks

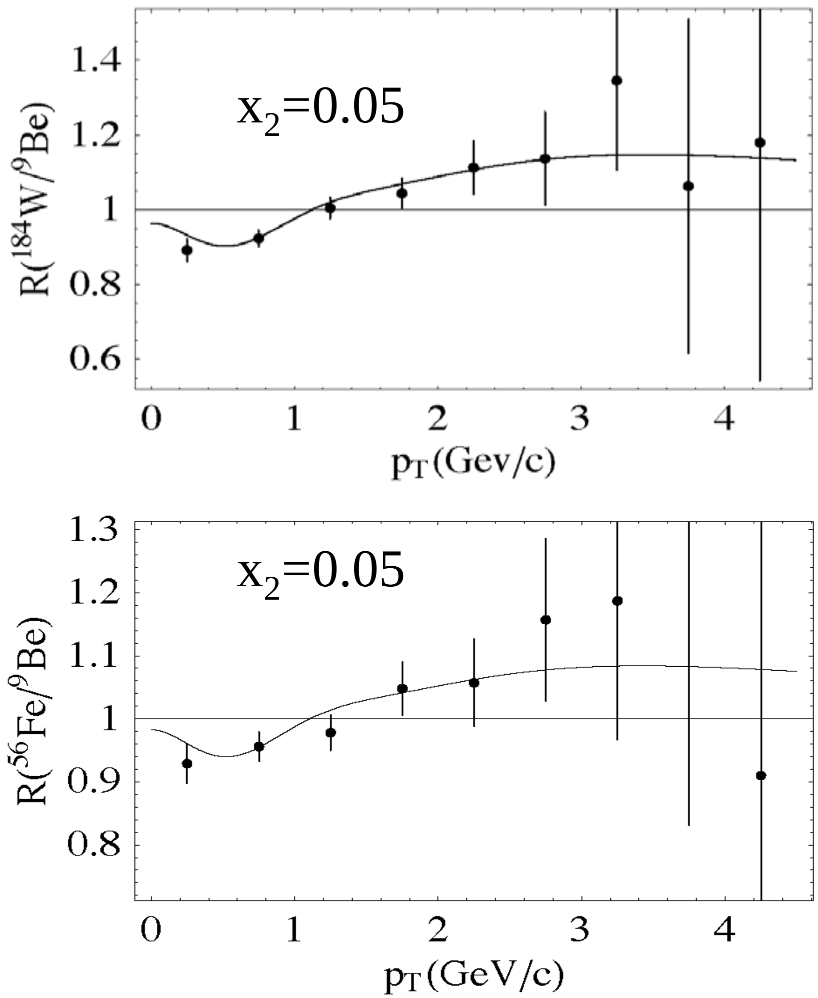
- Suppression at low $p_T$ and enhancement at high $p_T$
- Universal behavior for Drell-Yan, light quarks, heavy quarks - Cronin effect

Theory is in good shape, e.g. :

- Curves shown from Johnson, Kopeliovich, et al, initial state scattering of color dipoles
- Vitev, initial state multiple scattering

There is an energy loss connected with multiple scattering, scale strongly depends on energy loss model

E866 p+A→Drell-Yan



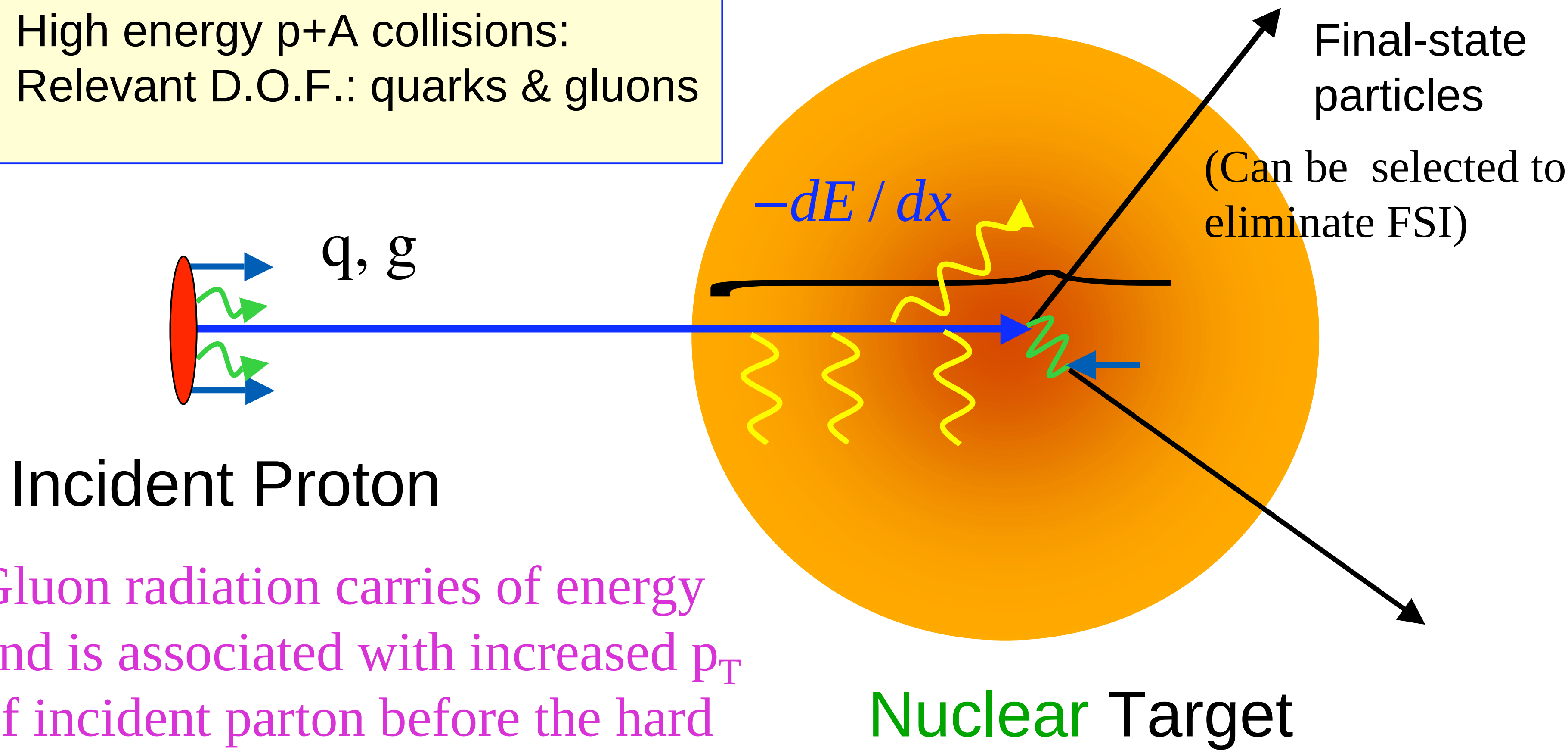
# Now for the fresh part

- Need to nail down the relative importance of shadowing versus energy loss
- Ivan has developed an integrated approach using pQCD to calculate these nuclear effects

  $\rightarrow$ demonstrates energy loss is important
- We suggest possible direct measurements of energy loss at RHIC and Fermilab

# The Basic Idea of Initial-State Energy Loss and Multiple Scattering

High energy p+A collisions:
Relevant D.O.F.: quarks & gluons

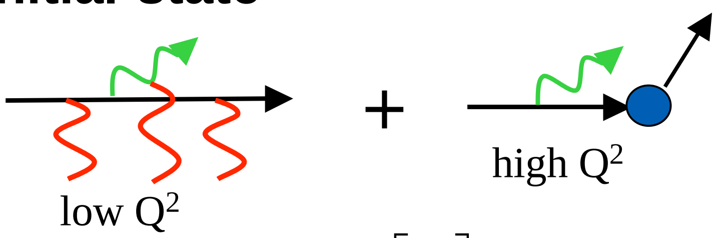



Gluon radiation carries of energy and is associated with increased $p_T$ of incident parton before the hard collision

For collinear (low $p_T$) gluons, scattering is coherent!

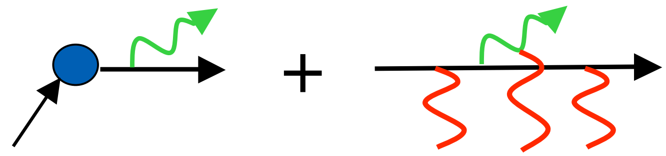
# Calculating Energy Loss in Large Nuclei (Vitev)

**Initial-state**




$$-\Delta E \sim \alpha_{\rm strong} \times \left[\frac{L}{\lambda}\right] \times [E]$$

**Final-state**



$$-\Delta E \sim \alpha_{\rm strong} \times \left[\frac{\mu^2 L^2}{\lambda}\right] \times \left[\ln \frac{2E}{\mu^2 L}\right]$$

Most important: the interference pattern between the bremsstrahlung from hard and soft scattering!

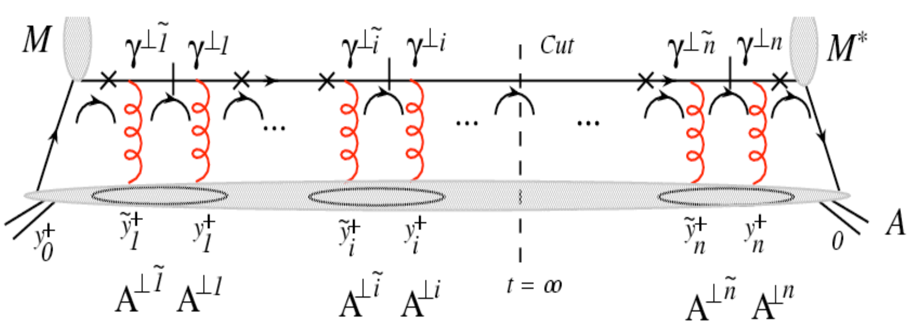
- Note that the initial-state energy loss is proportional to E
  $\rightarrow$ E loss is important at all energies !
- We have the theoretical tools to solve Initial-state E-loss

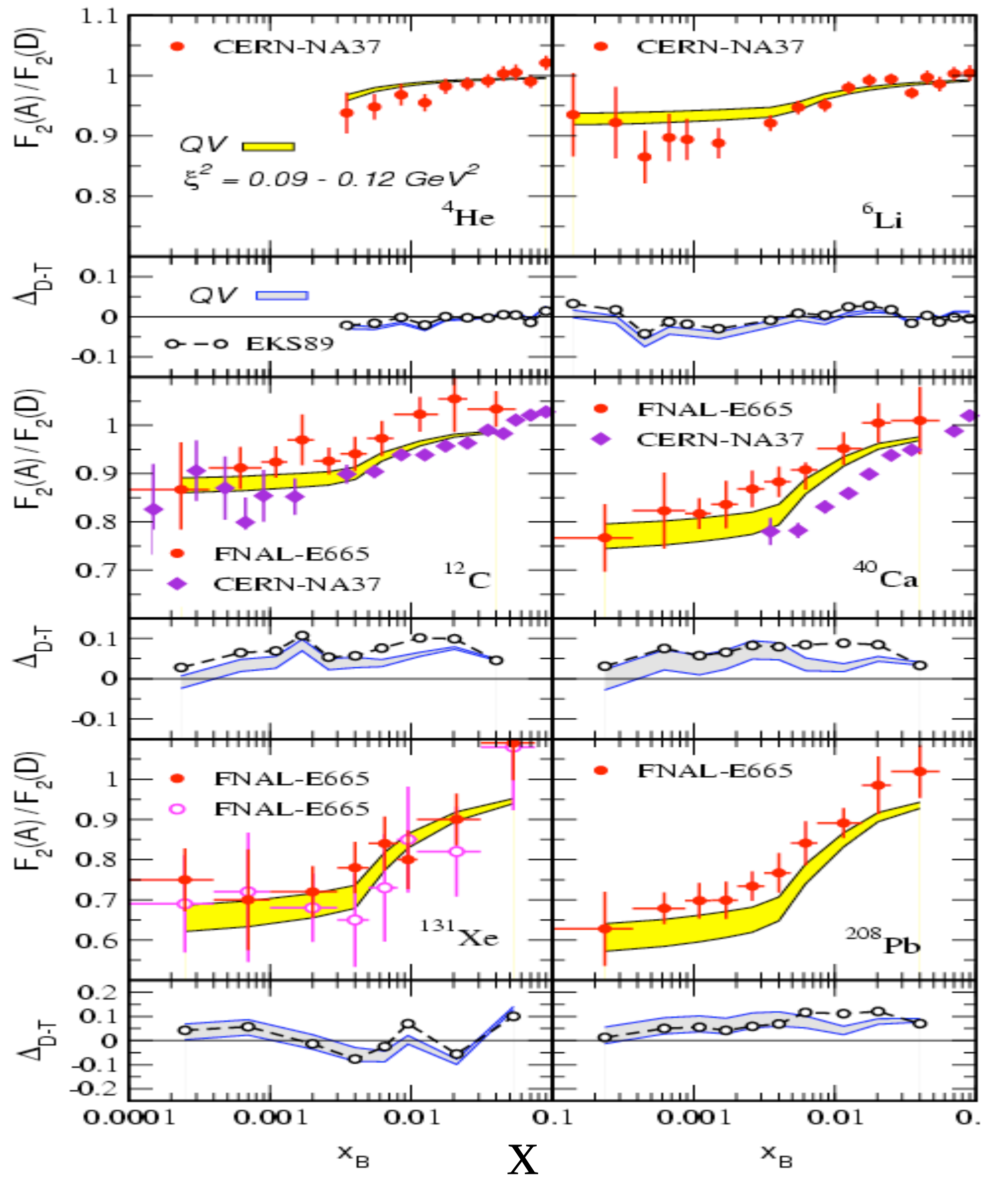
- Robust theoretical pQCD calculations of many-body scattering effects

# Calculation of nuclear shadowing in DIS from coherent final-state scattering (Vitev)

First principles calculation of quark shadowing in DIS using perturbative QCD does well

Note that this is not an initial state effect (gluons in nucleus are not changed) !

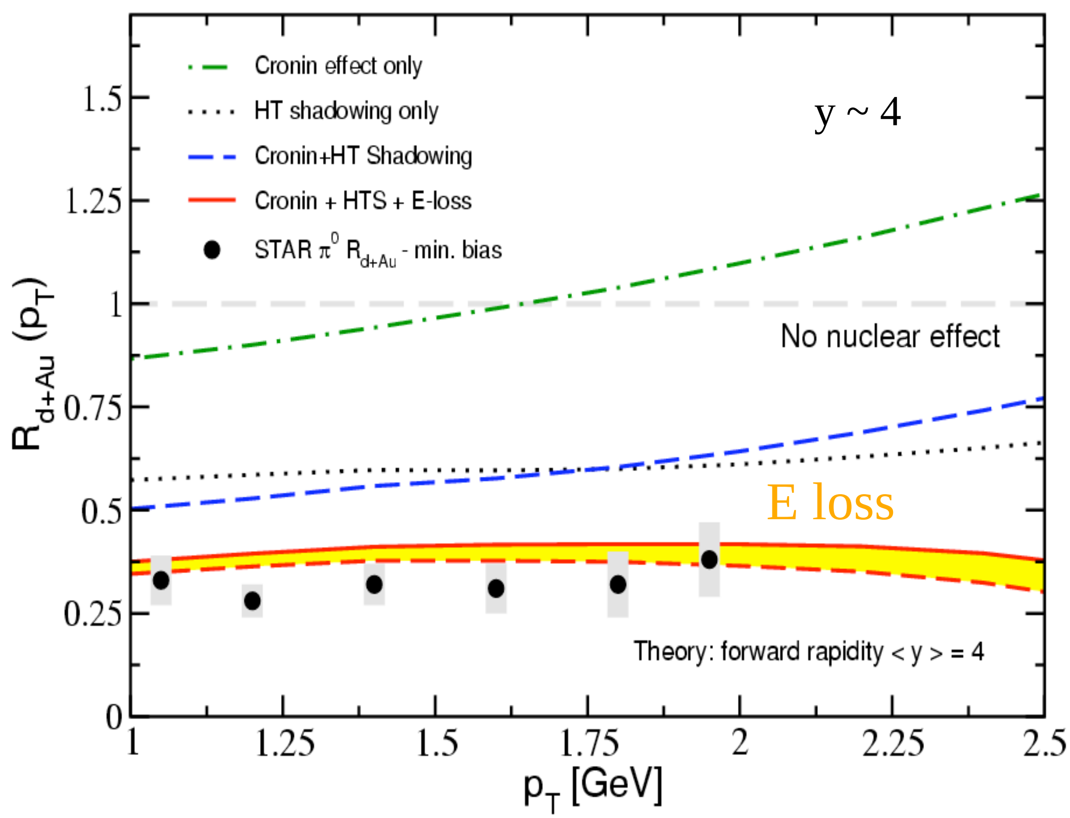


# Results for d+Au $\rightarrow \pi^0$ at forward rapidity at RHIC (Vitev)

Calculation includes :

- Cronin effect (initial state multiple scattering)
- Dynamical shadowing (coherent final state scattering) HTS
- Initial state energy loss (final state at these energies - negligible)

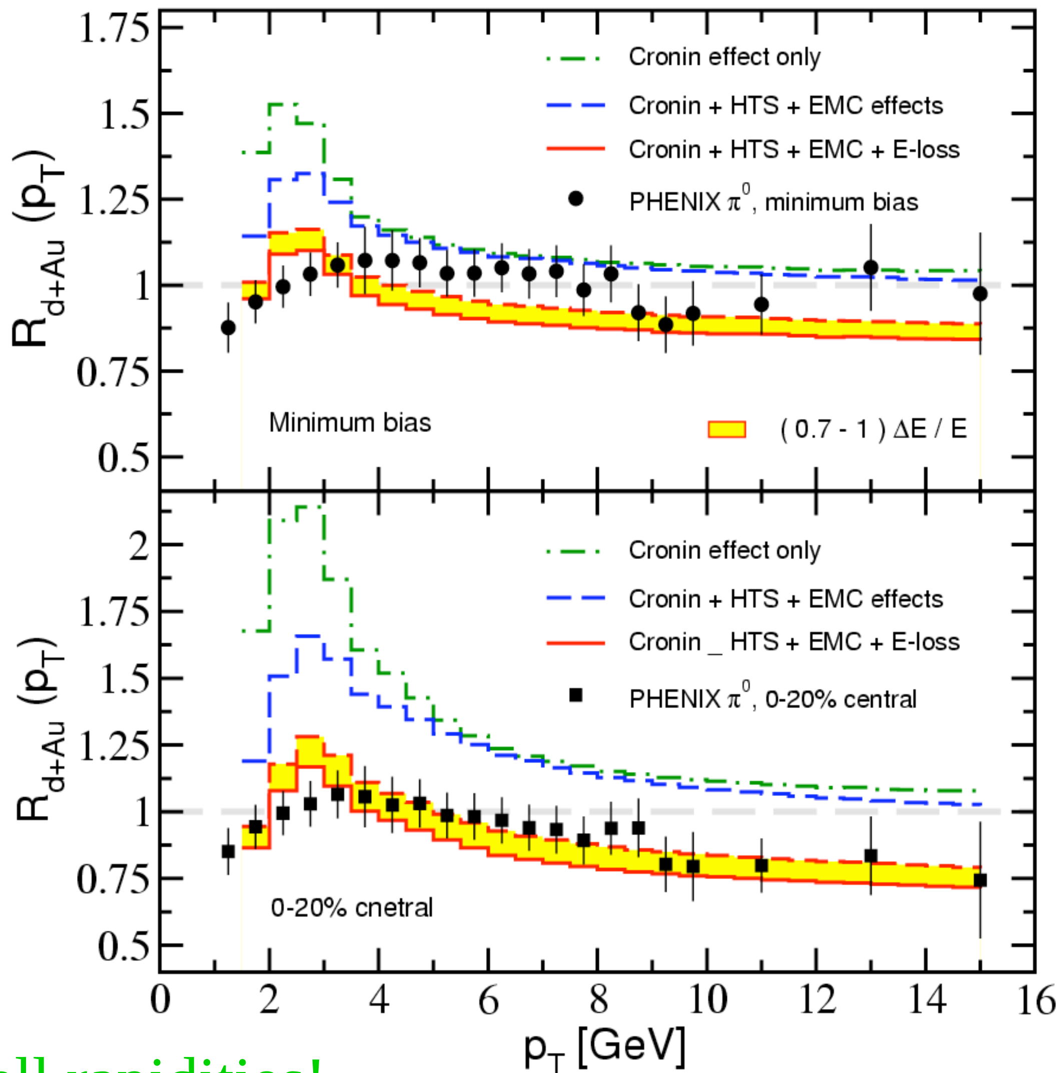



Energy loss is required.

Theory shows energy loss is important at all jet energies!

# Calculations for Mid Rapidity (Vitev)

Minimum bias: difficult to discern cold nuclear E loss, due to large contribution from the peripheral collisions



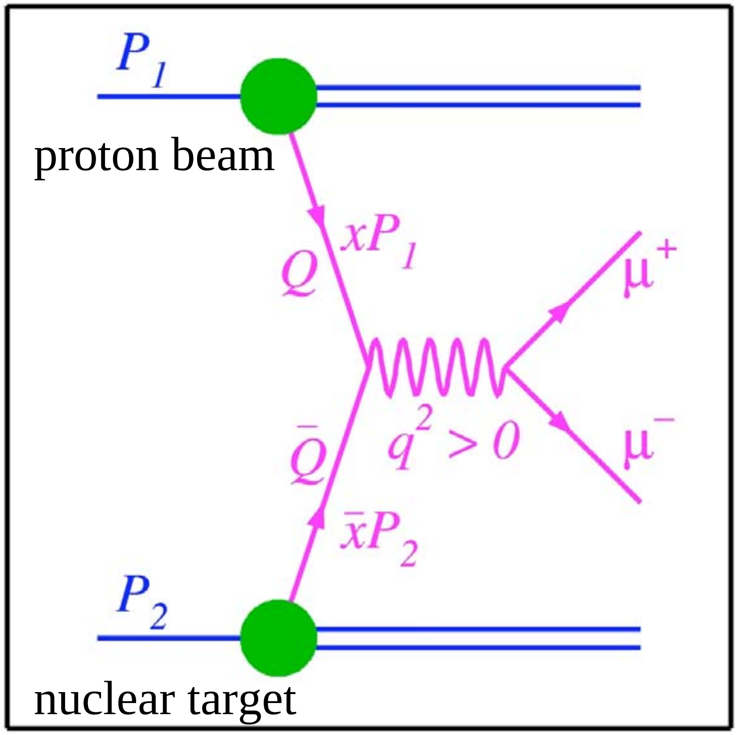

Central: clearly favors large cold nuclear matter E loss

→ Energy loss important at all rapidities!

# Use p+A→Drell-Yan to Measure Energy Loss

$$q + \overline{q} \rightarrow \gamma^* \rightarrow \mu^+ + \mu^-$$

Drell-Yan Process




Has only initial-state like effects for p+A :

- Shadowing of anti-quark in target
- Energy loss of incoming beam quark

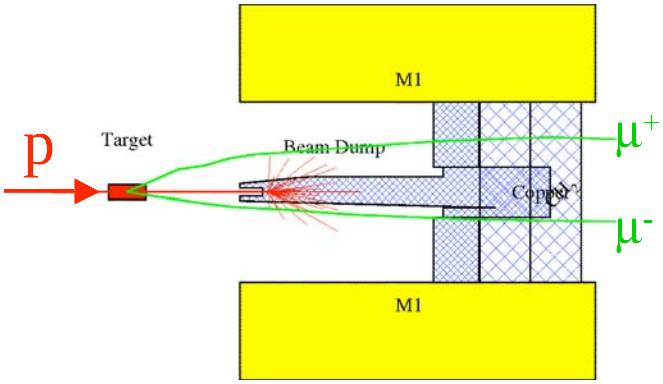
By lowering beam energy to 120 GeV, can completely eliminate shadowing!

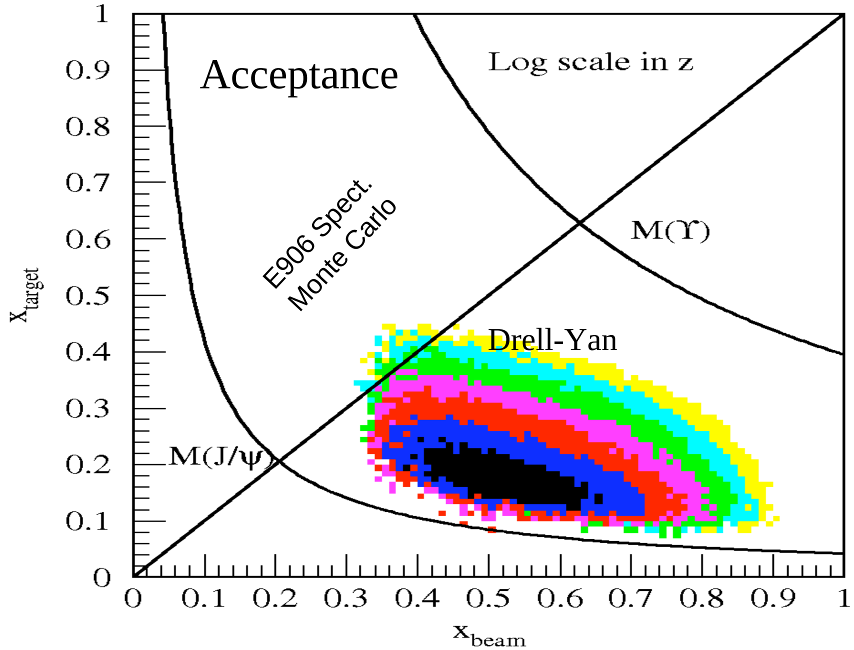
Cross sections calculable at next-to-leading order in pQCD :

$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9x_1x_2}\frac{1}{s} \times \sum_i e_i^2 \left[q_{ti}(x_t)\bar{q}_{bi}(x_b) + \bar{q}_{ti}(x_t)q_{bi}(x_b)\right]$$

# The E906 Experiment at Fermilab

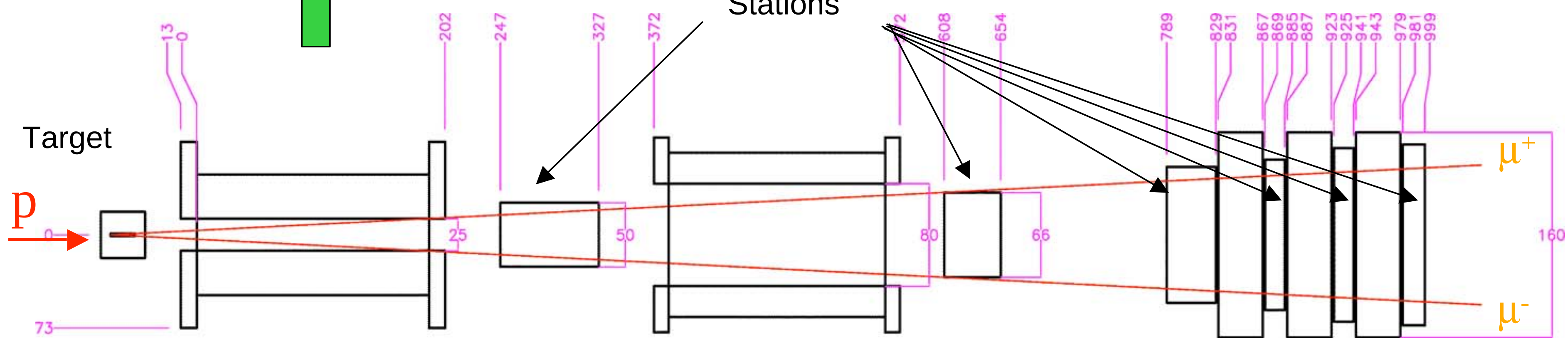
$p+A \rightarrow$ Drell-Yan




Beam energy of 120 GeV eliminates shadowing region

Tracking/Triggering Stations



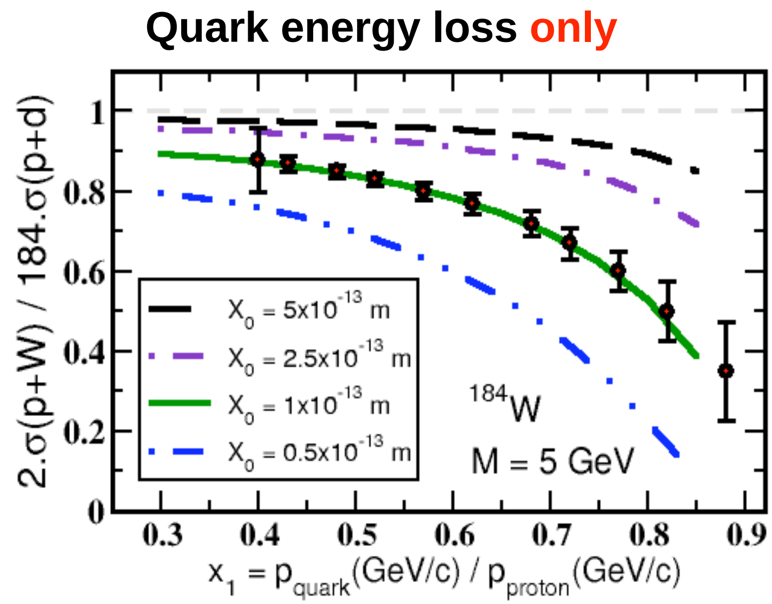

1st magnet sweep

2nd magnet momentum analysis

# E906 experimental sensitivity to quark energy loss

- For radiation lengths $X_0 = 1 \times 10^{-13}$ m achieve sensitivity ~ 20%

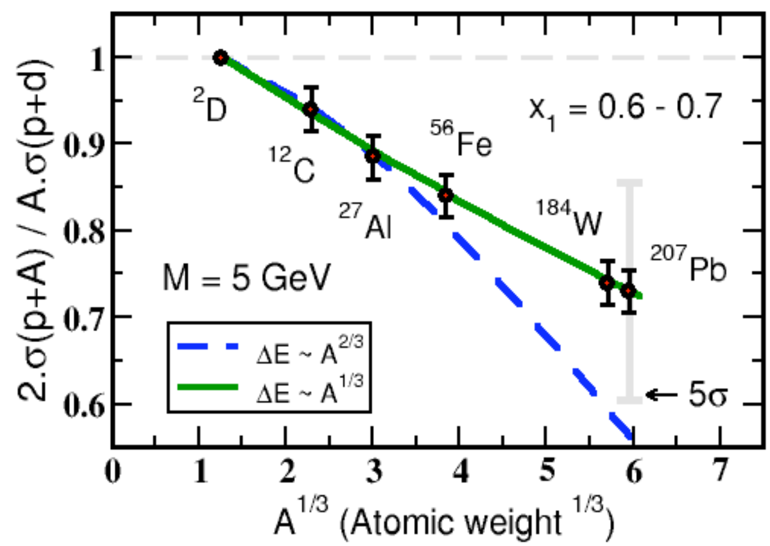
| Non-QCD | $X_0(W)=3.5\text{x}10^{-3}$ m |
|---|---|




- Clearly distinguish between leading models for L dependence of E-loss (5σ)

$$-\Delta E \sim A^{1/3} \ (\text{or} \ \sim L)$$

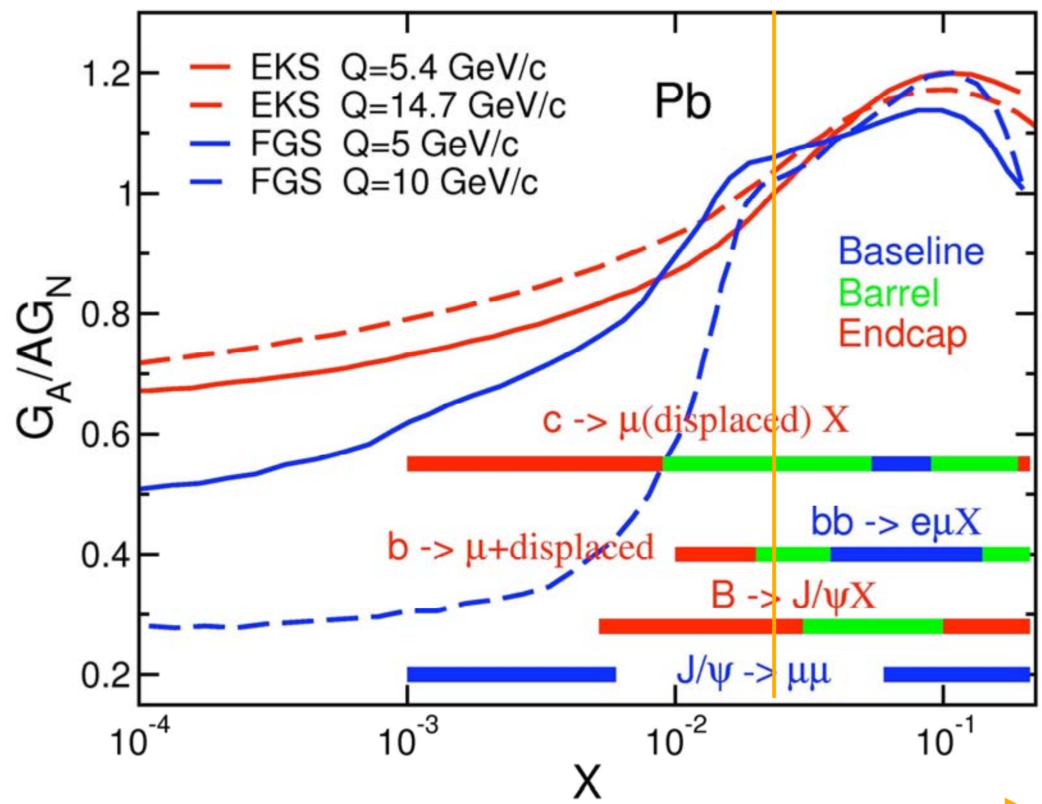
$$-\Delta E \sim A^{2/3} \ (\text{or} \ \sim L^2)$$



# Measurement of gluon energy loss at RHIC?

Need $Q^2$ large enough to avoid shadowing region :

- J/ψ and open charm at large $p_T$
- Upsilon and open beauty, esp at y=0
- Jets with large $p_T$




Out of shadowing region

Quarkonium also states have complicated final state interactions

## Parameters in Ivan's calculations:

- Shadowing - scale (strength) of higher twist per nucleon
- Energy loss and Cronin (coupled) from momentum transfer per unit length ~.12-.15 $GeV^2/fm$ for quarks, .6 $GeV^2$ for quark in nucleus. Gluons = 9/4 * quarks